CFD Simulations of the Madison Dynamo Experiment and Comparison of Dynamo Growth Rates

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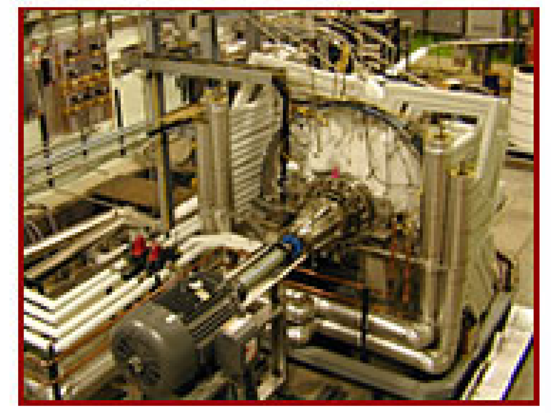
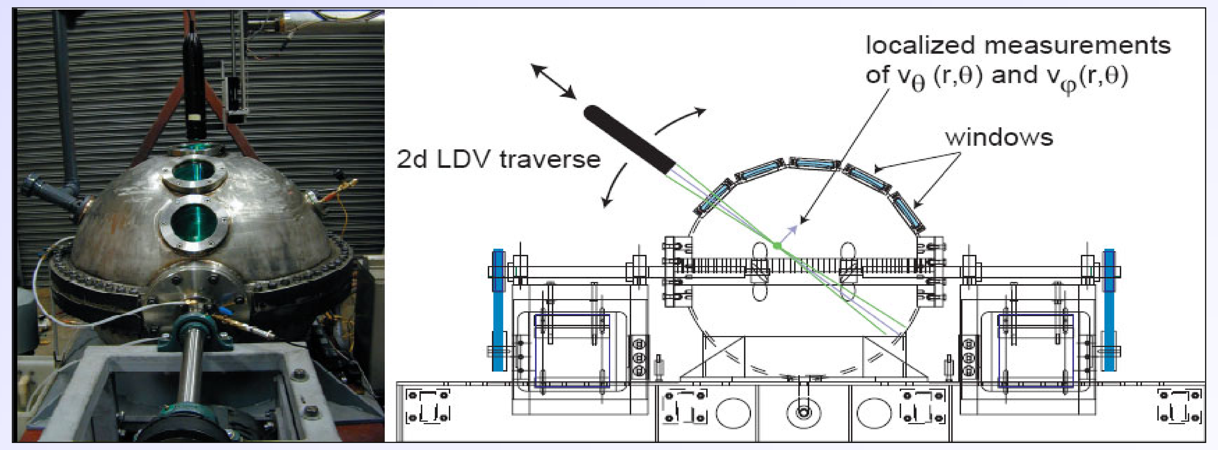


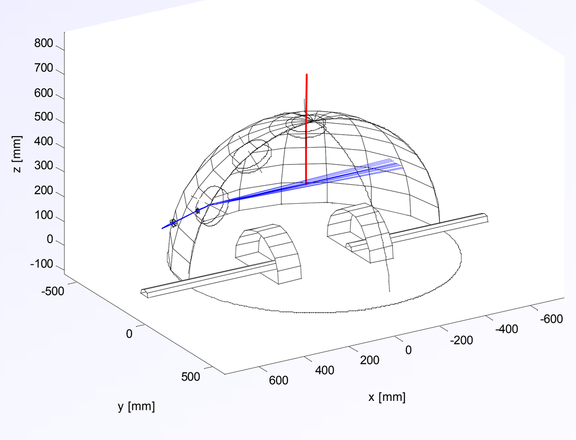
Introduction

The Madison Dynamo Experiment is studying the self-generation of magnetic fields called dynamos. Dynamos can form from the flows of conducting liquids or plasmas and are of particular interest to the understanding of the magnetic fields generated by the Sun, the Earth, and the Galaxy. The experiment consists of a 1 m diameter stainless steel sphere filled with liquid sodium. Turbulent flow is produced from two, axially aligned, counter-rotating impellers. In addition to the liquid sodium experiment, an identically scaled (based on geometry and fluid properties) water experiment is also used to study the flow characteristics. The water experiment has several ports that allow the use of laser Doppler velocimetry (LDV) for measuring flow conditions. Optimum conditions for the growth of magnetic fields and dynamos are highly sensitive to the flow geometries.

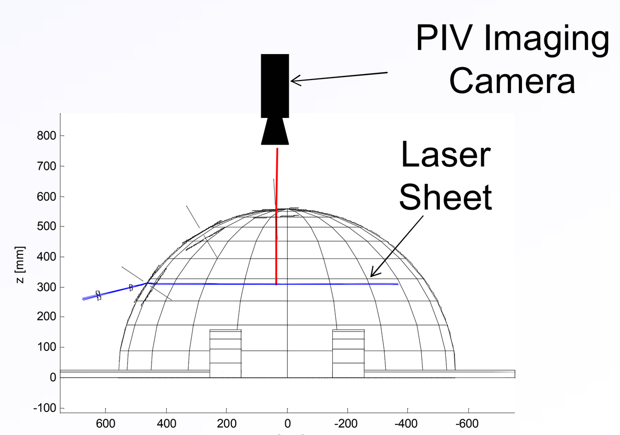
Experimental Setup



Pictured above is a schematic of the Madison Dynamo water experiment that is utilized to study the flow characteristics of the sodium experiment. An MHD (Magneto-Hydro-Dynamics) code has been created to predict the growth rates from a two dimensional velocity plane.



Illustrations of the recent PIV setup used to image a plane in order to obtain a 2D velocity field.



Objectives of CFD Simulations

The objectives of the CFD simulations are to:

1) Understand the flow characteristics of the experiment throughout the entire domain, thus including areas that are inaccessible by experimental techniques.

2) Understand how the flow field is affected by different geometrical parameters, primarily, the introduction of both an equatorial baffle and 6 adjustable, poloidal baffles.

3) Use data from the simulations for input to the MHD code to understand how the geometrical parameters affect magnetic growth rates.

4) Design modifications to the experiment that can optimize the conditions for the production of magnetic dynamos.

Abstract

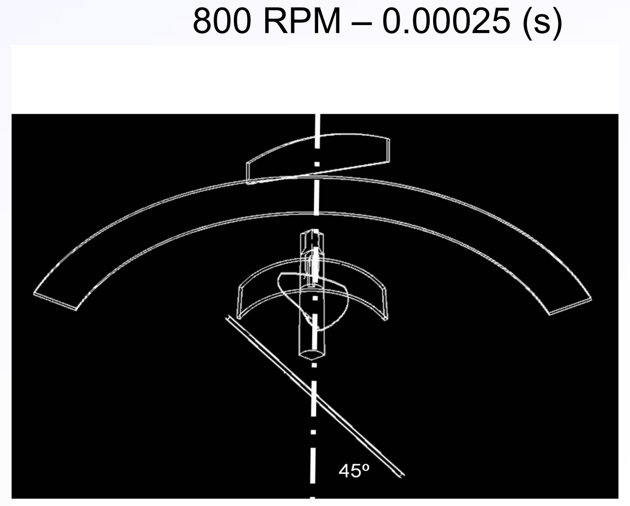
The Madison Dynamo Experiment is designed to study the growth of magnetic fields called a dynamo. The flow characteristics of the dimensionally similar water experiment have been modeled using the computational fluid dynamics (CFD) software *Fluent*. Results from the simulations are used to confirm flow characteristics measured by the laser doppler velocimetry (LDV) system and to gain insight into regions that are inaccessible via LDV. The results from the simulations can also be used as input into the MHD code to predict the threshold for Dynamo onset. The CFD simulations – in conjunction with the MHD Dynamo prediction code – can be used to guide modifications to the experiment before costly changes are physically implemented. Results show that the implementation of both equatorial and poloidal baffles will intensify the double vortex flow, thus having a positive impact on the growth rates. Additional work includes the use of particle imaging velocimetry (PIV) to obtain 2D velocity fields in a number of regions throughout the experiment which can be used to further corroborate the LDV and CFD flow field measurements.

Simulation Setup

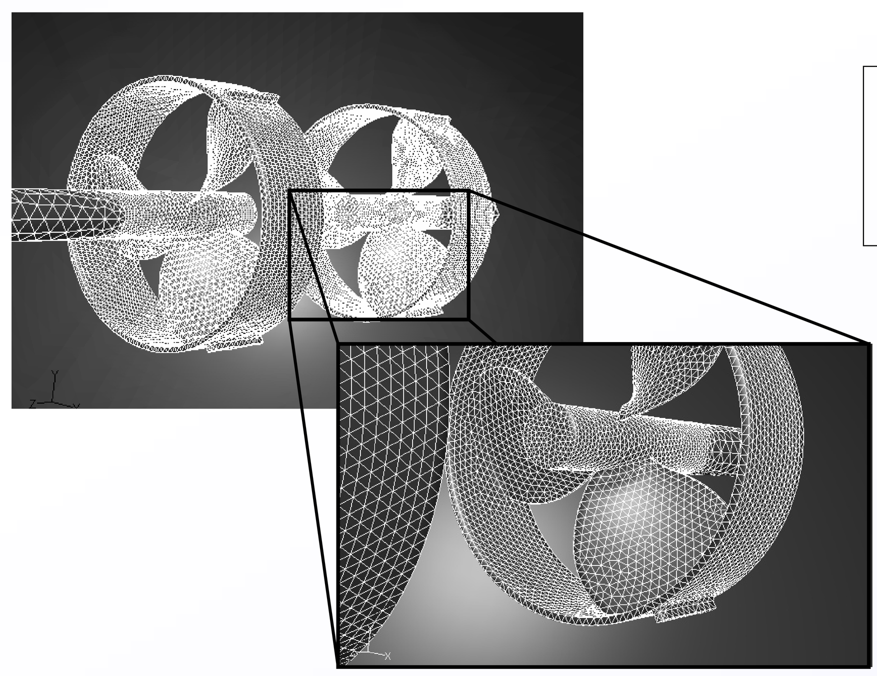
Fluent Solver with Gambit Mesh Generation

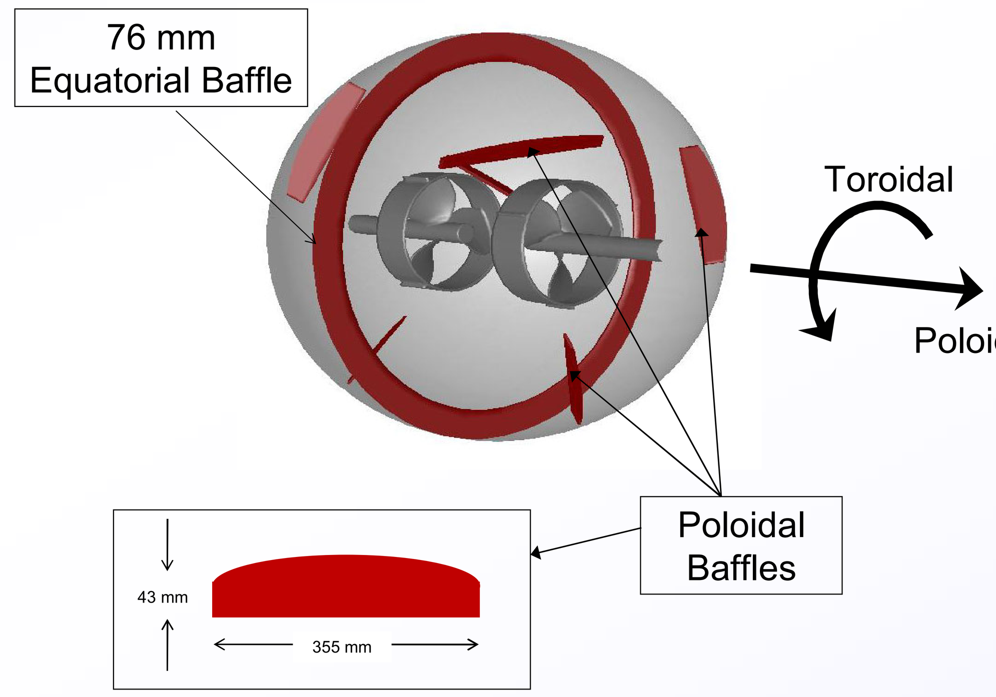
Models
Time: 1st Order Implicit
Viscous: Realizable, k-epsilon turbulence model
Δt's: 200 RPM – 0.001 (s)
800 RPM – 0.00025 (s)

Discretization Schemes
Pressure: Standard
Momentum: 2nd Order Upwind
T.K.E.: 2nd Order Upwind
T.D.R.: 2nd Order Upwind



Shown above is a depiction of the angle used to measure the orientation of the poloidal baffle





Shown above in red are the different baffles that have been modeled in order to observe their effects on the predicted dynamo growth rates.

To the left is a close up of part of the mesh used for the simulations. The mesh was generated in Gambit. Approximately 1,000,000 mesh elements were used.

Validation

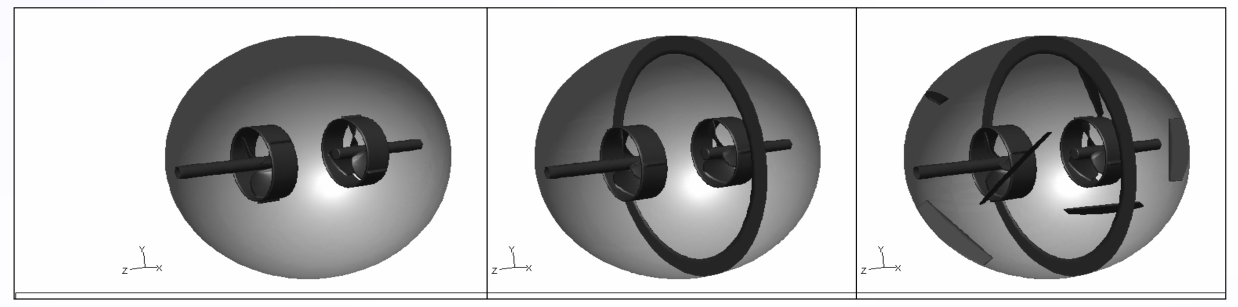
For validation purposes, the *Fluent* results were compared to experimental measurements taken from the LDV and select locations imaged via PIV. The agreements were satisfactory as is outlined in the table to the right.

Comparison of velocities at the location of the PIV imaging window for the three methods. (200 RPM Co-Rotating Propellers)

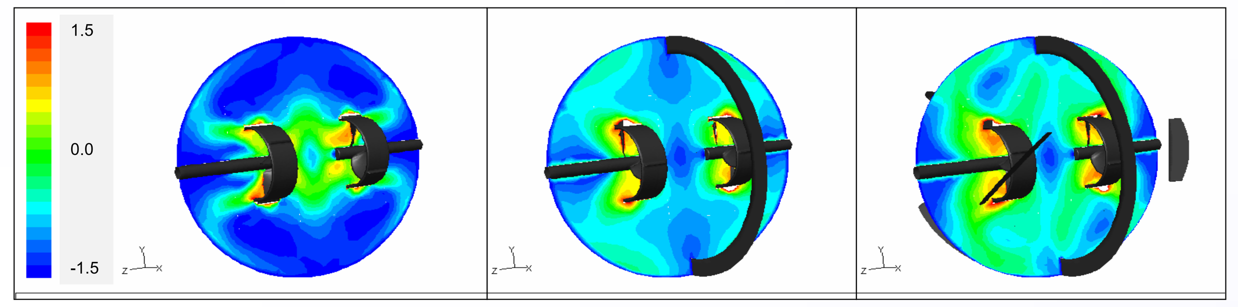
Method	Average Velocity (m/s)
LDV	.90
PIV	.82
Fluent	.79

Results

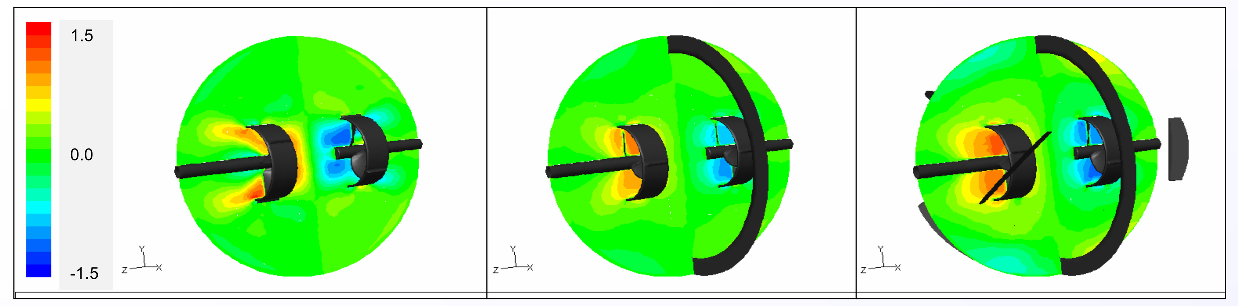
200 RPM Counter-Rotation



Above are the geometries for the three simulations performed.



Above are plots of the velocity magnitude on a single plane slicing the axis of the propellers.



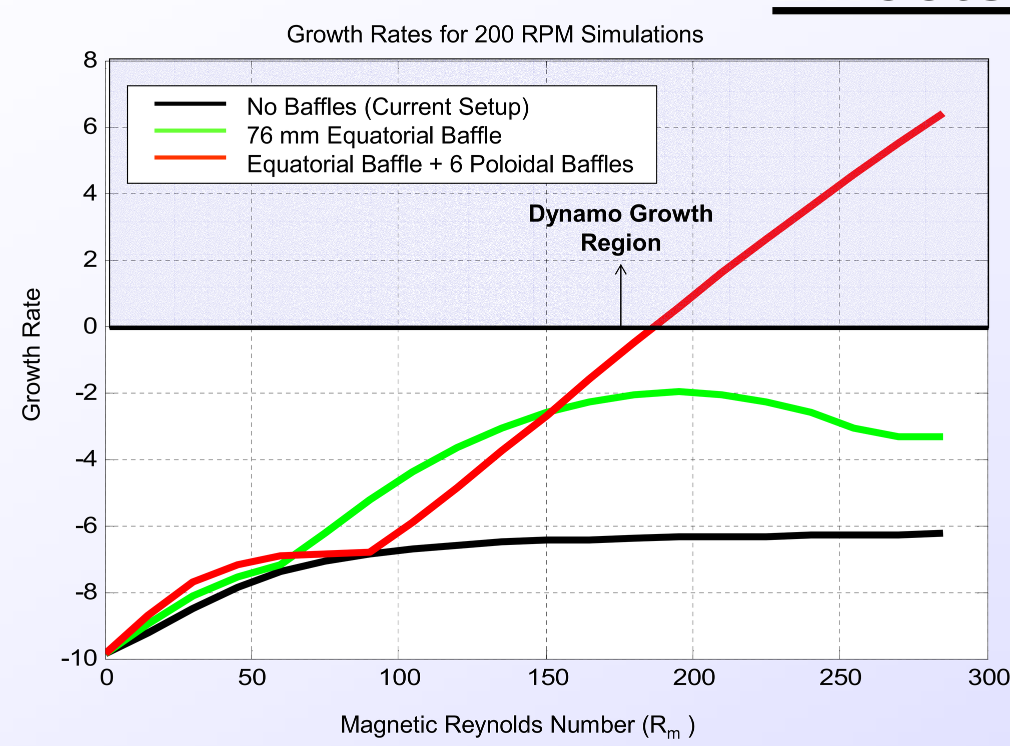
Above are plots of the axial (poloidal) component of the velocity on a single plane slicing the axis of the propellers. Right is a table outlining some turbulent quantities. The intensity is defined as the ratio of the root mean square of the velocity fluctuations to the mean flow velocity.

Even in the early stages of analyzing the simulation data, some key trends emerge in the flow fields from the addition of baffles. Notice in the lower sequence of images displaying the axial component of velocity how the addition of the poloidal baffles converts toroidal flow into poloidal in the regions near the baffles. This may intensify the double vortex flow that is thought to be favorable for the production of intermittent magnetic fields. This can be seen in the lower right two images as the velocities increase in the outer portion of the four quadrants of the plane. Another trend that was spotted was a decrease in turbulent quantities as the number of baffles was increased, especially with the addition of the poloidal baffles as seen in the table below.

Volume averaged turbulent quantities.

200 RPM Simulations	Turbulent Kinetic Energy (m^2/s^2)	Turbulent Dissipation Rate (m^2/s^2)	Intensity (%)
No Baffles	0.07	0.45	17.24
Equatorial Baffle	0.07	0.25	20.25
Poloidal Baffles	0.02	0.12	11.32
800 RPM Simulations	**Turbulent Kinetic Energy (m^2/s^2)**	**Turbulent Dissipation Rate (m^2/s^2)**	**Intensity (%)**
No Baffles	0.71	15.82	50.91
Equatorial Baffle	0.42	6.22	48.38
Poloidal Baffles	0.10	4.82	17.59

Effects on Growth Trends



The MHD code is used to predict the growth rate as a function of the magnetic Reynolds number, R_m, defined as:

$$R_m = \mu\sigma a V$$

where
μ = Permeability of free space
σ = conductivity of liquid sodium
a = characteristic size
V = characteristic velocity (taken as the maximum velocity found in the flow)

The growth rates are predicted from velocity data over 2D flow fields. The 2D data is generated from the 3D simulation by averaging the x- and y-velocities on 13 theta planes over 120 °.

Discussion

The results from the CFD simulations supply an enormous wealth of data and information about the flow characteristics of the Madison Dynamo Experiment. Preliminary analysis of the data for the three simulations performed thus far show some interesting trends, primarily in the growth rates upon the addition of the poloidal baffles. The poloidal baffles have the effect of converting toroidal flow into poloidal flow when placed at an angle of 45 ° with respect to the axis of the propellers. **The combination of the equatorial and poloidal baffles serve to intensify the double vortex flows, and appears to be favorable for dynamo production as confirmed by the calculated growth trends.** In fact, this seems to outweigh the decrease in turbulent quantities which is also generally thought to be favorable for dynamo production. Future work will include simulations for baffles oriented at angles of 30 ° and 60 ° to see if there is an optimal orientation of the poloidal baffles for dynamo growth.